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Trions as a probe of spin injection through II–VI magnetic/non-magnetic heterointerface

M. Ghali[a,*], J. Kossut[a], E. Janik[a], M. Kutrowski[a], Ł. Kłopotowski[b], M. Potemski[c], F. Teran[c]

[a]Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland
[b]Institute of Experimental Physics, Warsaw University, ul. Hoża 69, 00-81 Warsaw, Poland
[c]Grenoble High Magnetic Laboratory, F-38042 -Cedex 9, Grenoble, France

Abstract

We report on an efficient injection of spin polarized electrons from CdMgMnTe diluted magnetic semiconductor to non-magnetic CdMgTe quantum well structure. The electron spins were able to diffuse keeping their polarization memory for distances larger than 2000 Å. Study of the optical properties of trions is shown to be a new, highly sensitive detection tool of spin injection.

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Keywords: Diluted magnetic semiconductors; Trions; Spin injection

1. Introduction

Manipulation of electron spins is a basic ingredient of the new field of spintronics. The ability to exploit these spins in semiconductors promises new devices with enhanced functionality, such as high speed spin-polarized field effect transistors or logic gates in the emerging field of quantum computation [1]. This new class of devices involves injection of spin-polarized electrons through a magnetic/non-magnetic interface, with the spins being able to maintain the memory of their polarization during the transport in the non-magnetic semiconductor. At the present stage of development a sensitive spin polarization detection is, moreover, essential. Recently, efficient spin injection into semiconductors has been achieved utilizing either diluted magnetic [2] or ferromagnetic semiconductors [3] even in lattice-mismatched structures [4,5]. In all these cases spin polarized carriers have been injected into GaAs non-magnetic semiconductor structures due to the large spin coherence length observed in these materials [6]. The detection of those coherently transmitted spins has been recorded by observing polarized excitonic luminescence from non-magnetic quantum well QW utilized as spin injection detector.

*Corresponding author. Tel.: +48-22-843-1331; fax: +48-22-843-1331.

E-mail address: mohsen@ifpan.edu.pl (M. Ghali).

In this work we study transmission of spin-polarized electrons in CdMgTe non-magnetic semiconductor where spins originated from a diluted magnetic CdMgMnTe spin injector. Moreover, the main feature of this study is that we use negatively charged excitons X^- as a new probe for spin detection. Negatively charged excitons or trions in two-dimensional systems have been evidenced experimentally in 1993 [7] and have been the subject of very intensive studies [8–10] since then. Here we exploit the unique properties of trions that are due to their highly sensitive spin dependent formation character.

2. Experiment

The structure under study consists of a CdTe/$Cd_{0.92}Mg_{0.08}Te$ heterostructure with type I band alignment grown by molecular beam epitaxy on (100) oriented SI-GaAs substrate. A relatively wide CdTe quantum well (QW) with 150 Å width (assuring narrow lines in luminescence spectra) is confined between an abrupt band gap $Cd_{0.92}Mg_{0.08}Te$ barrier in one side. On the other side, a graded band gap barrier of $Cd_{1-x}Mg_xTe$, x ranging between 0.08 to 0.25, has been grown using the digital alloy method [11]. On the top of the latter barrier, a 380-nm-thick quaternary compound layer of $Cd_{0.72}Mg_{0.25}Mn_{0.02}Te$ diluted magnetic semiconductor (DMS) was grown, which serves as a source of spin

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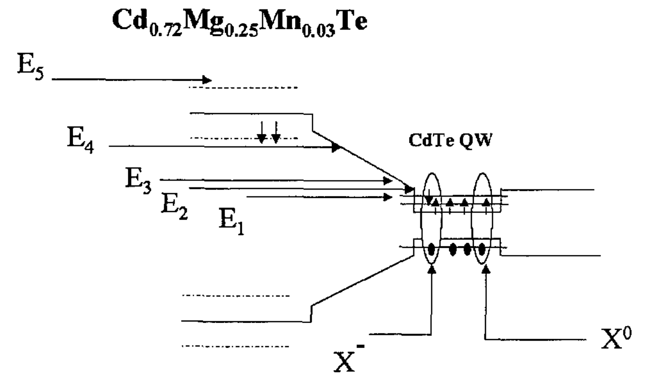

Fig. 1. A schematic diagram of the band alignment of the sample structure. Thick long arrows indicate absorption into different regions using different excitation energies. Dashed lines show the giant Zeeman splitting of CdMgMnTe bands.

polarized carriers. Fig. 1 shows a schematic diagram of the band alignment of the entire structure. The structure was intentionally undoped. However, due to residual impurities we may expect present of excess electrons in the QW of approximately 10^{10} cm^{-2}. The graded band gap spacer barrier between the QW and the spin injector was intended to enhance carrier diffusion into the QW.

Magneto-photoluminescence experiments were carried out on this structure in magnetic fields up to 13 T at the temperature of 1.8 K. Selective excitations in the QW, in the non-magnetic barrier and close but above the magnetic layer band gap have been performed using Ti:sapphire, He–Ne and Kr^+ lasers, respectively. Care was taken to keep the exciting power for each excitation line to precisely 1 mW. Auxiliary photoreflectivity experiments have been performed.

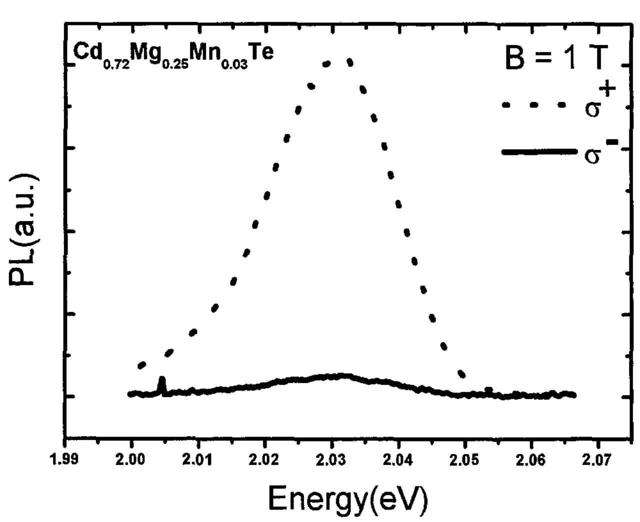

Fig. 2. Circular polarized PL of $Cd_{0.72}Mg_{0.25}Mn_{0.02}Te$ spin injector material under excitation by 2.18 eV in both (a) σ^+ and (b) σ^- detections in magnetic field 1T.

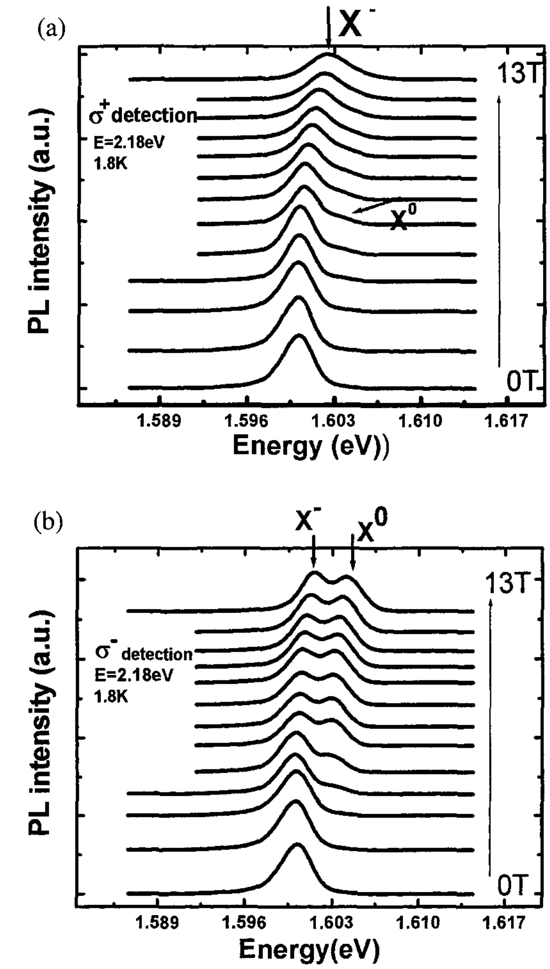

Fig. 3. PL spectra from the CdTe QW under excitation with 2.18 eV in different magnetic fields (from Zero till 13T). The detection was analyzed in both (a) σ^+ and (b) σ^-. Neutral exciton (X^0) is clearly pronounced at high magnetic fields starts from 3.6 T. The lower energy satellite peak is assigned to X^- trion. Note that both X^0 and X^- are circularly polarized in reversed directions.

3. Results and discussions

First, we confirmed by the reflectivity and PL measurements that the $Cd_{0.72}Mg_{0.25}Mn_{0.02}Te$ layer indeed shows a large Zeeman splitting (~35 meV at 5 T) between the spin-up ($m_j = 1$) and spin down ($m_j = -1$) excitons (i.e. it displays a giant spin splitting characteristics of DMS). Fig. 2 shows the photoluminescence from $Cd_{0.72}Mg_{0.25}Mn_{0.02}Te$ in σ^+ and in σ^- detection at 1T. As we can see, all optically pumped electrons in this layer relax to the lower Zeeman level producing a system of completely polarized excitons and, therefore, really completely polarized electrons [12]. This effect arises due to the presence of Mn^{2+} in the material that greatly facilitate the spin-flip processes. This feature, in fact, makes CdMgMnTe as an efficient spin injecting system. Fig. 3a,b shows the evolution of the PL spectra from the 150 Å CdTe QW at 1.8 K as a function of a

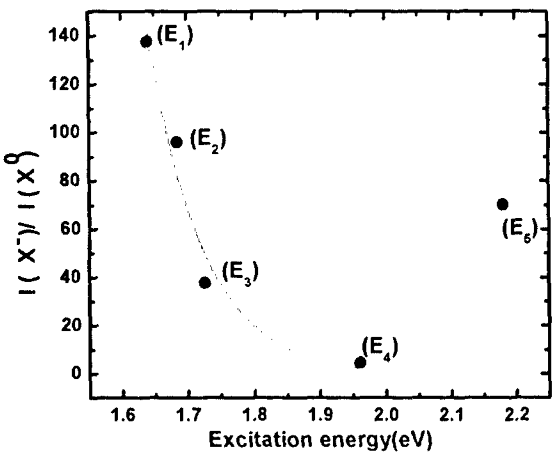

Fig. 4. The density ratio between X^- trion and neutral exciton (X^0) when photo-absorption occurs inside the QW (E_1), in the non-magnetic barrier (E_2, E_3, E_4) and above the spin aligner band gap (E_5). The decay of the ratio is clearly seen when the absorption is being in the non-magnetic regions (barrier and QW) while a re-enhancement of the ratio occurs when absorption occurs in the magnetic layer (the spin injector). Symbols represent data points while line is a guide to eyes.

magnetic field B in both σ^+ and σ^- detection, respectively. In these experiments unpolarized laser light with energy 2.18 eV has been used to excite the structure close to but above the CdMgMnTe band gap. As we can see, at $B=0$, the spectra are dominated by a strong peak at 1.600 eV with a small satellite ~3.4 meV at a higher energy. This satellite becomes gradually more pronounced with an increasing magnetic field in the σ^- polarization. This polarization behavior is confirmed in additional photoreflectivity measurements (not shown here). We assign the high-energy peak to neutral exciton recombination (X^0) while the lower one to a negatively charged exciton (X^-). The details of X^- identification will be shown elsewhere. The presence of trions in our intentionally undoped structure, showing their clear signature in the optical properties, can be ascribed to background n-type impurities in the structure. This effect has been observed in other recent studies in GaAs [13], CdTe [14] and ZnSe [15] structures. We estimate from the dissociation energy of the trions in our structures that the excess background electrons in the QW to be $\sim 3\times 10^{10}$ cm^{-2} [16]. The intense X^- peak at zero fields indicates the high probability of X^- formation. Fig. 4 shows the integrated intensity ratio of X^- to that of exciton (which we assume to be proportional to the densities of X^- and X^0, respectively) under different excitation energies: above, in the non-magnetic barrier, and inside the QW in the magnetic field of 0.5 T.

Let us discuss first what happens when the excitation energy does not exceed the band gap of the magnetic layer (2.03 eV in the absence of the magnetic field). In Fig. 4—under various excitation energies, E_1, E_2, E_3, E_4—it is clearly seen that the X^-/X^0 intensity ratio decays with the excitation energy increasing gradually from the QW band edge. This behavior implies a reduction of the excess electrons in the QW. This is, in turn, related to the fact that most of the absorption events occur in the non-magnetic barrier region when excitation is above the QW edge [17]. As in intentionally n-type doped GaAs-AlGaAs QWs, the internal electric fields created both by the ionized donors and the excess electron charges in the well tend to separate the photo-created electron–hole pairs excited in the barrier [18]. It is suggested that the holes are swept into the well where they can recombine with the excess electrons in the QW, while the photo-excited electrons are trapped by the ionized impurities in the barrier [19]. Those electrons that, nevertheless, enter into the well have a 'wrong' spin (i.e. the same spin with $m_j = +1/2$ corresponding to the lowest Zeeman component of spin splitting conduction band in the non-magnetic material) as those already present in the well, therefore, not being able to form a stable trion in a singlet state.

Let us now see what happens when the absorption of the exciting light occurs in the magnetic layer (the spin injector in our structure). With excitation energy E_5, we notice in Fig. 4 a significant increase of the X^- to X^0 intensity ratio. We have to keep in mind that there is a reversal of sign of the g-factor of the photoexcited electrons in this magnetic regions ($g<0$ for the CdMgTe barrier and CdTe QW) while $g>0$ for CdMgMnTe magnetic spin aligner. The formation probability of X^- trion is proportional, specifically, to the number of spin-down ($m_j = -1/2$) electrons in the QW system. These can be easily supplied if there is an efficient and spin preserving transfer of electrons from the spin injector to the QW layers. This leads to an important conclusion that this enhancement of X^-/X^0 density ratio is due to spin polarized electrons diffusing, in the spin down state, from the magnetic spin aligner (CdMgMnTe) to the CdTe QW via 2000 Å of graded band gap non-magnetic CdMgTe spacer. These polarized electron spins, which are in the 'correct' spin state; $m_j = -1/2$; (i.e. reversed in direction to those contained already in the CdTe QW) are captured by confined electron–hole pairs (excitons) inside the QW increasing the formation probability of X^- trions.

In conclusion, we have shown possibility of optically injecting electron spins from II–VI magnetic semiconductor to non-magnetic CdTe QW using a non-ordinary probe (negatively charged exciton). The trion X^- can be efficiently used as a highly sensitive spin detector due to its spin dependent formation character.

Acknowledgments

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